Report on a workshop on electromagnetic induction methods for UXO detection and discrimination

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To decrease cost and increase reliability and efficiency of unexploded ordnance (UXO) environmental remediation, government research and development programs and industry efforts seek to establish a practice of UXO location using modern digital survey systems, sound geophysical survey procedures, and postprocessing of data for enhanced detection and discrimination. The new practice will replace most traditional "mag and flag" type UXO location surveys that typically use analog instruments, where all detected targets (anomalies) must be investigated (i.e., excavated). Several factors, both technical and nontechnical, drive and justify the change in practice: (1) digital data allow maintenance of a permanent record of the locations of targets and sensor signatures over targets; (2) digital data will typically have higher dynamic range (hence higher signal-to-noise ratios) than the analog data that rely on audio or visual output; (3) digital data allow and facilitate postprocessing to enhance signatures for improved detection and for UXO discrimination and identification; and (4) digital data acquisition is more likely to be repeatable by surveys at different times and by different operators. Item 1 is required/mandated by regulatory agencies. Items 2-4 will enhance the probability of buried UXO detection and improve the regulatory and public acceptance of geophysical UXO surveys. Finally item 3, UXO discrimination and identification, can result in significant cost reduction, since 70-75% of current remediation costs result from digging (excavation) at locations of false alarms (non-UXO).

Total field magnetometry (TFM) and electromagnetic induction (EMI) are the two classes of geophysical methods generally applied for UXO location and characterization. TFM methods generally consist solely of measurement of the total field, although various field gradients are sometimes measured/determined. Although limited to a passive measurement of the magnetic field induced in ferrous targets by the "static" earth's magnetic field, there is demonstrated potential for UXO discrimination using magnetometry (e.g., Billings et al. 2002). EMI methods, however, are more versatile in terms of the type of measurement, frequency or time range of the measurements, and the configuration of the transmitters and receivers. While there are advantages and limitations of each of the methods, the methods are complementary (Figure 1), and it is generally agreed that there are significant advantages to making both types of measurements over a UXO survey site. Simple time-domain EMI (TDEM) and frequency-domain EMI (FDEM) systems may operate at only one transmitted frequency or sample only one time gate of the target transient induction response. Simple EMI systems have been used extensively for general environmental site characterization and, in the case of the TDEM systems (e.g., the Geonics EM-61), used extensively for UXO surveys. While effective for detection, simple EMI systems have only limited potential for discrimination applications. The relatively new broadband systems, such as the Geonics EM-63 and Zonge nanoTEM TDEM systems (Figure 2) and the Geophex GEM-3 FDEM system (Figure 3), have considerable potential for UXO discrimination application (e.g., Pasion and Oldenburg 2001; Grimm 2003).

The Strategic Environmental Research and Development Program (SERDP), the Environmental Security Technology Certification Program (ESTCP), and the Army Environmental Quality Technology Program (EQT) have a significant past and ongoing investment in basic and applied research, development, and technology demonstrations of innovative EMI systems and approaches for UXO detection, discrimination, and identification. Recognizing the considerable potential of EMI for enhanced UXO detection and discrimination, the three programs jointly sponsored an EMI workshop, 4-5 February 2004, in Annapolis, Maryland, U.S. Although there is coordination among the programs, there was a clearly recognized need to review the status of EMI and establish a roadmap for future investments to advance the application of EMI for UXO applications. The 72 workshop participants included 28 from government agencies and 44 from private industry and academia. In addition to selected presentations and breakout discussion sessions, 25 poster displays allowed detailed informal discussions of

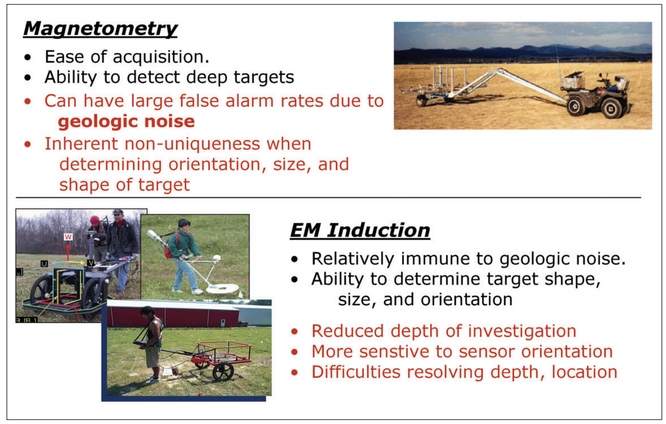


Figure 1. Comparison of strengths and limitations of total field magnetometry and electromagnetic induction for UXO location (adapted from Pasion et al., 2003).

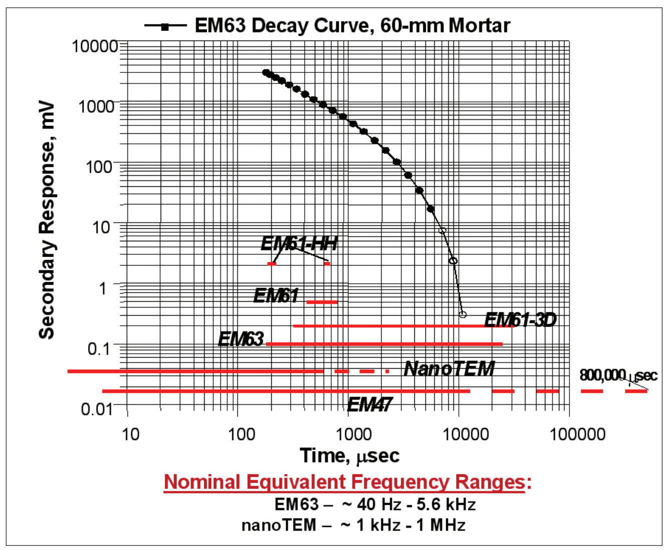


Figure 2. Example of a time-domain signature of a UXO item (oriented horizontally) and nominal measurement times of TDEM systems used for UXO surveys (from Butler et al., 2003).

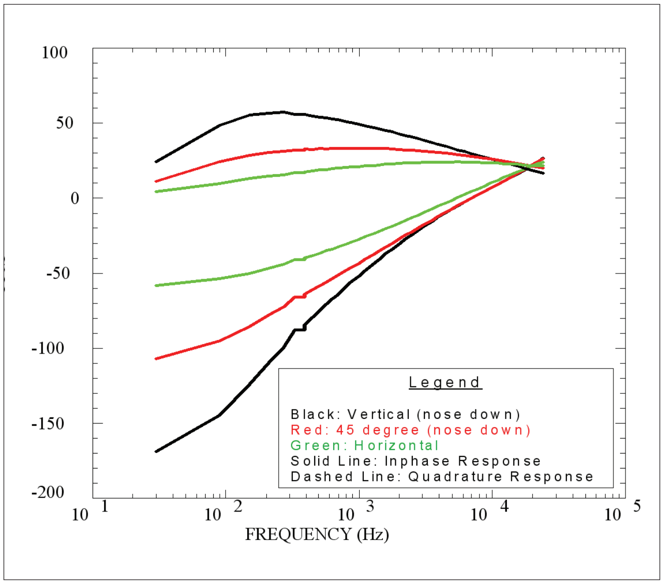


Figure 3. *Example of frequency-domain signatures of a 60-mm mortar at different orientations relative to the sensor.*

individual projects.

Anne Andrews, SERDP UXO program manager, coordinated the organization of the EMI Workshop to facilitate practical information flow between principal investigators and to allow government managers and investigators to identify gaps in understanding and technology that should be addressed by future research. In addition, Jeff Marqusee, SERDP/ESTCP director, and John Cullinane, EQT program director, interacted with an Organizing Committee (John Ballard, Jay Bennett, Thomas Bell, Dwain Butler, Larry Carin, Leslie Collins, Dean Keiswetter, Frank Morrison, Herbert Nelson, Doug Oldenburg, Robert Selfridge, and Skip Snyder) to plan the workshop.

Organization and format. Potential attendees were invited to submit short "read-ahead summaries" on their EMI UXO application efforts that included hardware development of system components, signal processing, modeling and inversion, discrimination algorithm development, field data collection for system and modeling assessments, system demonstrations, and system and data integration. The summaries concisely communicated the essence and diverse nature of EMI work directed to UXO. They were grouped into three general categories: EMI sensors/systems (15), EMI modeling and data (7), EMI data processing/inversion (13), where the numbers in parentheses indicate the number of summaries received in each category.

The three general categories listed above were the basis for the format. The first day included two state-of-practice presentations and overviews of the three topic areas:

- UXO cleanup case studies (Robert Selfridge, U.S. Army Corps of Engineers)
- Current performance in testing (George Robitaille, US Army Environmental Center)
- Overview of sensors (Frank Morrison, University of California, Berkeley)
- Overview of modeling and data (Thomas Bell, AETC Incorporated)
- Overview of signal processing/inversion (Leslie Collins, Duke University)

Following the presentations, breakout sessions were organized around the three topic areas, with attendees assigned to a group in order to insure diverse backgrounds and interests in each group. The charge to each session chair was to lead a group discussion and then summarize the state of the science in the area, identify technical limitations and gaps in understanding and capabilities, and identify key information needs from and critical performance issues relevant to the other topic areas.

The second day included three breakout groups with the identical mandate to consider the broad category of systems integration, with particular attention to addressing the issues and questions identified by the topic area groups. Systems integration was broadly defined to include topics such as system design, operational procedures (e.g., systematic survey versus cued survey versus intermediate options), platforms, navigation and positioning, and real-time versus postprocessing for detection and discrimination.

Sensors (session chairs Frank Morrison and Skip Snyder). The term "sensor" was defined to be the complete EMI system, consisting of transmitters (Txs), receivers (Rxs), power supply, and all associated electronics. With the progression to more quantitative systems, it is critical to carefully characterize the transmitter waveform, including the on/off ramp for TDEM, and to monitor it during survey execution. Generally two forms of transmitters are used for UXO survey applications: small (≤ 1 m^2), mobile, air-cored, multi-turn loops, generally with Rxs that move with the Txs, and large (100 - 10 000 m^2), static, air-cored, loops, with mobile Rxs that systematically move inside the large loop.

Some key conclusions and recommendations regarding Txs:

1) Three-axis illumination of targets by Txs is important because it is impossible to estimate anisotropic polarizability with a single loop static Tx; however, a multi-axis Tx illumination system is not currently available.
2) Depth of detection scales with Tx loop size.
3) Tx weight (including loop, driver electronics, and power supply) is approximately constant for a given Tx moment.
4) Accurate current waveform measurements are required for TDEM interpretation.
5) Duty cycle is an important variable for magnetic soil identification.
6) The Tx waveform can be tailored to maximize the bandwidth required for interpretation. Low frequency content is determined by base frequency, SNR, and survey speed; the response at low frequency/long delay times is desirable but difficult to measure in practice.

The most common type of EMI Rx is a small, air-cored induction coil. The induction coil can be designed to measure the time derivative of the magnetic field (dB/dt, critically damped) or the magnetic field (B, current or feedback). Some induction coils or solenoids have high permeability cores. Another option for an EMI Rx is a magnetometer (e.g., squid, fluxgate, magnetoresistive, or alkali-vapor total field).

Some key conclusions and recommendations regarding Rxs:

1) Rx arrays are desirable/and multi-axial measurements increase interpretation/discrimination potential.
2) No information is lost whether the measurements are of B or dB/dt, but numerical integration for B is unsatisfactory. B also has a larger time window (Figure 4) and a smaller dynamic range than dB/dt. B(t=0) is measure of target size. Primary field transient is worse for B than dB/dt, but the transient is reduced for magnetoresistive and squid sensors.
3) High permeability-core coils are temperature sensitive and have undesirable transient responses. Small air-core

Figure 4. Illustration of potentially larger time window for B, compared to dB/dt; transient decay computations for 37-mm "shell" model (3:1 aspect ratio), located 0.75 m below 1 m × + m Tx and for 37-mm sphere, compared to a half-space response (from Overview of Sensors Topic Area, Frank Morrison, EMI Workshop, 2004).

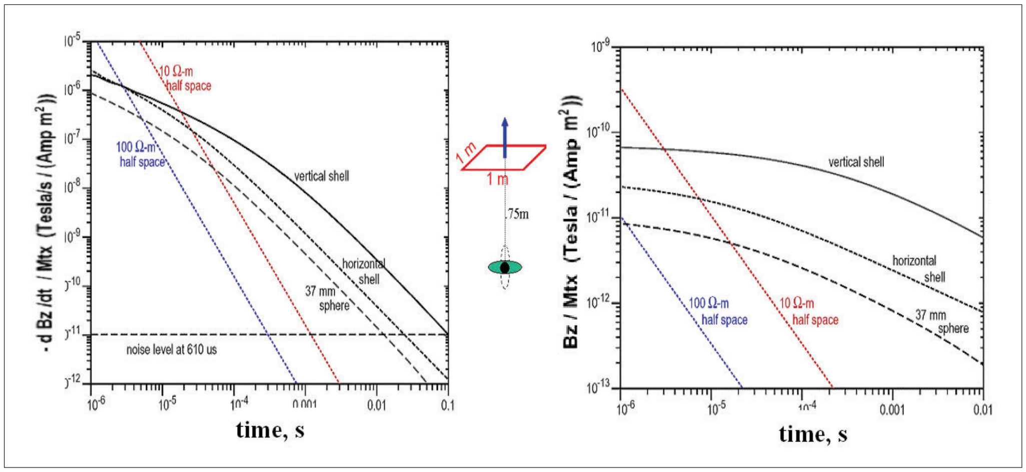
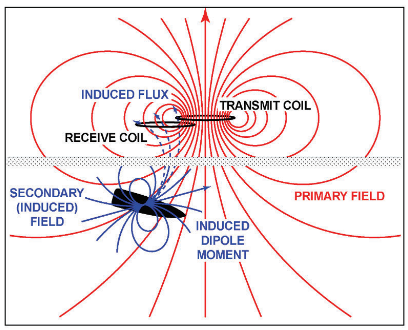


Figure 5. Illustration of EMI in a compact target with phenomenological models of the time decay and frequency dependence of the principal components of a point dipole magnetic polarizability tensor. The four fitting parameters in each model description are used in discrimination algorithms (adapted from Overview of Modeling and Data Topic Area, Thomas Bell, EMI Workshop, 2004).



TDEM:

$$L_i(t) = k_i(t+t_{oi})^{-\nu_i}\exp(-\alpha_i t);$$

FDEM:

$$\beta_i(\omega) = A_i\left\{S_i + \frac{(i\omega\tau_i)^{\gamma_i}-2}{(i\omega\tau_i)^{\gamma_i}+1}\right\};$$

where $L_i(t)$ and $\beta i(\omega)$ are the principal components of the magnetic polarizability tensor that describe the time or frequency dependence of the polarization of the compact target. For axially symmetri c targets, such as a cylinder or spheroid, $L_1(t) = L_2(t) \neq L_3(t)$, and similarly for the $\beta_i(\omega)$. For the axially symmetric TDEM case, for example, this model can be viewed as two orthogonal dipoles that decay independently (Pasion and Oldenburg, 2001).

coils have adequate sensitivity and bandwidth.

4) Bandwidth of 30 = t = 30 000 µs (30 = f = 30 000 Hz) is adequate for uxo characterization. Improved characterization with longer times/lower frequencies is possible with static systems.
5) A dual-mode TFM/EMI system is very desirable.

Additional issues and needs identified by the sensors session were:

1) System designers need target data (recovery depths, orientations, dimensions, geometry and material types).
2) Additional work is needed on role of Tx waveform versus extraction of target features.
3) Better access to a set of standardized targets (e.g., loops, spheres, spheroids, ...) and to standard ordnance items for prototype system testing is needed.
4) Studies of Tx-Rx configurations that minimize host response (e.g., for magnetic soils) are lacking.
5) A thorough analysis of system and background noise sources versus receiver type (e.g., platform, motion-induced, and ambient noise characterizations for available/common EMI systems) is needed.
6) Standardized measurement units or validated conversions must be developed.

Modeling and data (session chairs Thomas Bell and Larry Carin). While perhaps overly simplistic, there are two general classes of EMI response models for UXO: "detailed" models (e.g., finite element, boundary element, mean field, etc.) and basic response models (e.g., empirical, analytical, "physics-inspired", etc.). Detailed simulation of the EMI response of target models of arbitrary complexity, in terms of geometry and construction materials, allows fundamental insights into the desirable attributes of simpler or basic response models and allows detailed phenomenological studies for sensor design and development and EMI signature characterization approaches. Detailed models are generally too complex (require too long to execute and do not have simple attributes for characterization) for inversion of measured signatures for target properties. Analytical and empirical basic response models are generally parametric models that allow inversion of measured EMI target signatures for model parameters. The model parameters are related directly or empirically to physical properties of the target. The recovered parameters from inversion of basic response models are used in discrimination and classification algorithms (e.g., Bell et al. 2001).

Basic response models can be rigorous models of the EMI response of simple targets (spheres, plates, cylinders, spheroids) but are only approximate models for complex targets (including complex shapes and multiple material types). The most common basic response model is that of a point dipole target described by a magnetic polarizability tensor (Figure 5). In fact all practically implemented inversion algorithms rely on a point dipole target model. For many targets, such as the projectile illustrated in Figure 5, the point dipole target model works quite well. However, the point dipole model does not always accurately reproduce the spatial response patterns, particularly for targets buried less than a characteristic dimension in depth, and is problematic for geometrically complex targets and for composite-material targets. Two approaches for modeling target complexity, without resorting to detailed models, include (1) the use of multiple offset dipoles and (2) the standardized excitations approach. Each of these more complex response models better replicates the spatial response for composite targets, but is more difficult to implement in practical inversion algorithms.

Issues, open questions, and needed feedback identified in this session included:

1) Are the data being acquired adequate to validate the

models? What additional controlled datasets are needed for sensor design, testing, and validation? Is there a role or need for additional detailed datasets from free air test stands with variable positioning and target orientation capability? Can rigorous or detailed 3D models be used to generate "data" for model validation?
2) What is the value added of introducing new model complexity? Input from the other topic areas is needed to define value added by increased model complexity; i.e., can new model complexity better account for and use new sensor and data acquisition complexity?
3) How accurate are the various models and how accurate do they need to be? What are the limitations of the models as a function of the environment, sensor type and geometry, target type, etc.? How can model results best be used for sensor design and testing? What impact/effect do factors like sensor drift, accuracy, uncertainty, variability between sensors of the same design, etc., have on model fidelity? How robust are the models for handling variability of design and in-situ condition details of ordnance of the same type?
4) What is the role of environmental complexity on sensor performance and capability for UXO discrimination? Are magnetic soils, high conductivity sea water, and geologic heterogeneity serious problems? What is the impact of the geologic "half space", and is it important to include in models? How do metallic clutter (e.g., ordnance "frag", cultural metallic debris/trash) affect results? How do we handle cultural interference (e.g., fences, buildings, utilities, etc.); power lines; radio frequency sources).
5) After we know the effects of the geologic background on sensor response, can tools or procedures for "ground rejection" be developed?

The session included extensive discussion of information needs from and possible deliverables to the sensors and signal processing/inversion areas, with the goal of having a closed loop between the "communities" of research activity.

Participants also supported conducting a thorough assessment of the current capability to perform high-fidelity, detailed EMI modeling of complex and composite targets in a realistically complex geologic background. While detailed modeling of geometrically complex targets has been performed, it has generally been done with unrealistic assumptions, such as a uniform excitation field and essentially free-space conditions. The general consensus was that advancements to sensor design, modeling, data processing, inversion, discrimination algorithms, etc., could result from the enhanced phenomenological understanding that could evolve from such a detailed modeling effort.

Signal processing/inversion (session chairs Leslie Collins and Dean Keiswetter). The discussion revolved around preprocessing, characterization, classification, and documentation. This proved a very useful and constructive approach to discussing a very complex topic area. Under this categorization of the topic, inversion comes under characterization, which provides the information that is then used in the classification category to discriminate UXO-like targets from non-UXO-like targets and make decisions. Decisions are then "fed" to the documentation category, where reports such as the ubiquitous "dig list" are generated.

Briefly, the categories were defined to include, though not exclusively:

1) Preprocessing. Visualization, multisensor coregistration, signal-to-noise processing (including leveling, drift corrections, "de-spiking", etc.), automatic or manual anomaly (target) selection, quality assurance and quality control (QA/QC)
2) Characterization. Model selection (TDEM, FDEM, point dipole with polarizability tensor, multiple offset dipoles, standardized excitations approach, phenomenological models for time and frequency domain responses, etc). Position correction (e.g., due to roll, pitch, yaw). Target signature/source area selection or separation (in case of closely spaced or overlapping signatures). Target "co-registration" for multiple datasets. Inversion for target characteristics (parametric inversion, single sensor inversion, cooperative inversion, joint inversion, etc.).
3) Classification. Feature selection and down selection, such as parameters from inversion (location, depth, orientation, physical properties, magnetic polarizability tensor components), using procedures including exhaustive search strategies, physics and intuition, information theoretic approaches, and robustness assessments. Initial "training" (i.e., developing general correlations or connections to the real world through, for example, use of signature databases or documented demonstration test site results). Site specific "training" (i.e., developing site-specific correlations or connections to the real world, for example, by calibration test areas at specific sites or live site prioritized digs designed to maximize information return from dig results). Uncertainty and ambiguity characterization and mitigation (e.g., through quantification of inherent variability of EMI responses of ordnance items and associated effects on feature selection and down-selection, and by investigating alternate models and inversion methods that use a Bayesian approach with models having parameters with associated uncertainty). Decisions, for example, through matched filters or signature libraries, statistical/Bayesian classifiers (generalized likelihood ratio test, support vector machines, fuzzy clustering, etc.), neural networks, pattern recognition, rule-based classifiers.
4) Documentation. Setting the threshold for "dig" declaration, through experience, number of digs allowed, or statistical procedure based on the training data. Quantitative assessment of confidence in "dig"/"no dig" declarations. Report generation includes the "dig" list.

Some general observations and conclusions were:

1) Existing models, inversion approaches, and classifiers produce similar results for field data collected today. Data acquisition noise levels, position uncertainty/errors, and geologic "background noise" and heterogeneity are too high to accurately utilize higher fidelity models.
2) A well designed statistical framework is needed to assess model-based inversion performance. This will require probabilistic assessments (probability density functions) of geologic background noise, target variability, location errors, data acquisition strategies, etc.
3) Monte Carlo simulations can be used to study many aspects of the four signal processing and inversion categories, such as quantifying measures of data coverage and quality in terms of the various noise levels, assessments of errors in sensor position and orientation on data quality and classifier performance, determining the dominant parameters in ordnance/non ordnance decisions, and a study of decision rules and justifications for thresholds.

Systems integration (session chairs Jay Bennett, Dwain Butler, Herbert Nelson, Robert Selfridge). These sessions considered the broad range of systems integration issues mentioned previously, in light of the three focused sessions on sensors, models and data and signal processing/inversion. A simple definition of systems integration is a process of putting components and systems together in such a way that the total (integrated system) is greater or better than the sum of the parts. So systems integration could be as simple as integrating a positioning system (e.g., GPS) with a hand-held magnetometer system and a data processing system. A far more complicated example is the case of an airborne or marine survey system involving multiple sensor systems, full 3D position measurement systems, motion measurement and compensation, platform stabilization and steering systems, and specialized data acquisition/processing hardware and software.

Due to the broad nature of the systems integration topics and the limited time, the discussions were not tightly focused. Some key and recurring issues and conclusions of the systems integration sessions were:

1) A detailed, software-based EMI system simulator is feasible and desirable. A simulator should be used to test new and innovative EMI system designs; optimize Tx/Rx size, operating characteristics, numbers, orientations, spacings, etc; test EMI data acquisition scenarios, including time, position, hardware, targets, geologic background, processing; investigate optimal survey speeds for spatial resolution and sampling frequency, which will depend on the type/size of the ordnance present.
2) There is need to fully understand the performance characteristics of different platform designs, e.g., hand-held, man portable, and man-portable and towed multisensor arrays: analyze and design sensor layout on platforms to minimize mutual interference/coupling; assess and understand noise sources on platforms, including electronic noise, variable sensor orientation, sensor motion (including motion in the earth's magnetic field), positioning accuracy for individual sensors on platform, structural noise due to flexing and expansion/contraction of platform components, structural noise due to coil design, flexure, temperature variation, and EMI noise/interference from metallic components in and on the platform; better approach of assessing and quantifying platform performance; investigate mechanical approaches to improve platform stability and performance relative to motion induced noise, e.g., the known advantages of "long wavelength" motion noise, which may be achievable by various platform motion damping implementations.
3) Survey mode versus cued mode. Survey mode was defined as systematic coverage of an area with EMI measurements, while cued mode was defined as follow-on, small area high-density measurements around identified potential target areas. The cued mode obviates many systems issues, e.g., relative positioning errors, motion-induced errors, etc., resulting in truly coregistered data if multiple sensor types are used. No major sensor- or systems-related issues preclude cued mode operations; indeed new multisensor systems may open new possibilities for discrimination and identification. Cued mode may be particularly suited and justified for high threat or sparse target areas. The major trade-off is between time and cost versus benefit. A cost increase of greater than a few percent for geophysical surveys (relative to the nominal 10%) will be justifiable if the cued mode process can be demonstrated with a high success rate. Major improvements in survey mode success rate can be achieved if surveys are performed at a slower rate in order to improve signal-to-noise ratio and increase spatial measurement density.

Suggested reading. "Subsurface discrimination using electromagnetic induction sensors" by Bell et al. (*IEEE Transactions on Geoscience and Remote Sensing*, 2001). "Magnetic discrimination that will satisfy regulators" by Billings et al. (*Proceedings of the UXO/Countermine Forum,* 2002). "Enhanced discrimination capability for UXO geophysical surveys" by Butler et al. (*Proceedings of SPIE Vol. 5089, Detection and Remediation Technologies for Mines and Minelike Targets VIII*, 2003). "Triaxial modeling and target classification of multichannel, multicomponent EM data for UXO discrimination" by Grimm (*Journal of Environmental and Engineering Geophysics*, 2003). "A discrimination algorithm for UXO using time domain electromagnetics" by Paison and Oldenburg (*Journal of Environmental and Engineering Geophysics*, 2001). "Joint and cooperative inversion of magnetics and electromagnetic data for the characterization of UXO discrimination problems" by Paison et al. (*Proceedings of the Symposium on Applications of Geophysics to Environmental and Engineering Problems*, 2003). TLE

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